ANALYSIS

42(192), October 1, 2015

Discovery

ISSN 2278–5469 EISSN 2278–5450

Real-time flood forecasting for hydraulic risk management: the lateral flow representation issue

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Publication History
Received: 25 July 2015
Accepted: 06 September 2015
Published: 1 October 2015

Citation
Barbetta S, Moramarco T. Real-time flood forecasting for hydraulic risk management: the lateral flow representation issue. *Discovery*, 2015, 42(192), 45-51

ABSTRACT

An accurate forecast stage at river sections is of paramount importance to properly address Flood Forecasting and Warning Systems (FFWSs) operating in real-time. The forecast values can be provided by flood wave routing models to be implemented when gauged sections are operative along the channel. Different models have been proposed in the literature and the forecast can be approached by neglecting or involving the contribution of lateral flows. Among the latter, STAFOM-RCM (Stage Forecasting Model-Rating Curve Model) assumes a lateral contribution uniformly distributed along the reach (Barbetta et al., 2011). Therefore, the model application is not suitable for future stage prediction at hydrometric sections just located downstream river confluences. To overcome this issue, we propose a methodology that exploits the forecast stage provided by STAFOM-RCM at a gauged site on the tributary and the relationship between the stages recorded here and the ones at the downstream site along the main channel. The Paglia River basin, in central Italy, is selected as case study. The results indicate that the procedure can be useful to address real-time hydraulic risk management even at river sections located downstream important confluences, provided that gauged sites are operative along the tributary.

Keywords: flood forecasting, real-time, lateral flow

1. INTRODUCTION

Last decades showed the steady increase of damages due to flooding highlighting the need of developing effective measures to reduce the flood events impacts. To this end, structural measures (dikes, dams and flood storage areas) and non- structural (real-time Flood Monitoring and Warning Systems, FMWSs) may be used to mitigate the hydraulic risk.

As regards the latter, forecasting models, providing future estimates of the main hydrological quantities, represent one of the fundamental components of FMWSs. Traditionally, flood forecasting have been approached using rainfall-runoff or flood routing models. The former allow the forecast at the basin outlet starting from rainfall data and the forecast lead-time is generally identified by the time of concentration of the basin. The latter provide forecasts at a downstream end of river reaches with a forecast lead-time limited by the flood wave travel time; nevertheless they are more appealing for the limited data required and parameters involved.

For river reaches with negligible intermediate drainage area, flood routing models without incorporating lateral flow can be used (Moramarco et al. 2008, Perumal et al. 2011). However, for long river channels a model capable to quantify the lateral flow has to be considered and different approaches have been proposed in the literature, such as the use of rainfall-runoff modelling (Price, 2009), Artificial Neural Networks (Tayfur et al.,2007) and simplified methods relating upstream and lateral contribution (O'Donnell 1985). In this context, recently two flood routing models for stage forecast also incorporating lateral flow have been proposed: STAFOM-RCM (Barbetta et al., 2011) and RCM-RT (Barbetta and Moramarco, 2014). Both models assume a uniform lateral contribution along the reach and assess the lateral flow for unit channel length through a physically based approach starting from the continuity equation (Moramarco et al., 2005). Therefore, tributaries located immediately upstream the downstream gauged section of interest for the forecast, identify a non-optimal conditions for the applications of the models.

In this context, our aim is to propose a methodology for the forecast stage assessment at hydrometric sections on the main channel located downstream river confluences by exploiting the future stage predictions provided by STAFOM-RCM at gauged sites of the tributaries. The Paglia River basin, in central Italy, is selected as case study.

2. STAGE FORECASTING MODEL

The real-time flood routing model STAFOM-RCM (Stage Forecasting Model-Rating Curve Model) provides forecast stages by explicitly estimating at each time of forecast, t_f, the lateral flow along the selected reach (Barbetta et al., 2011) and is based on the coupling of two models (Figure 1):

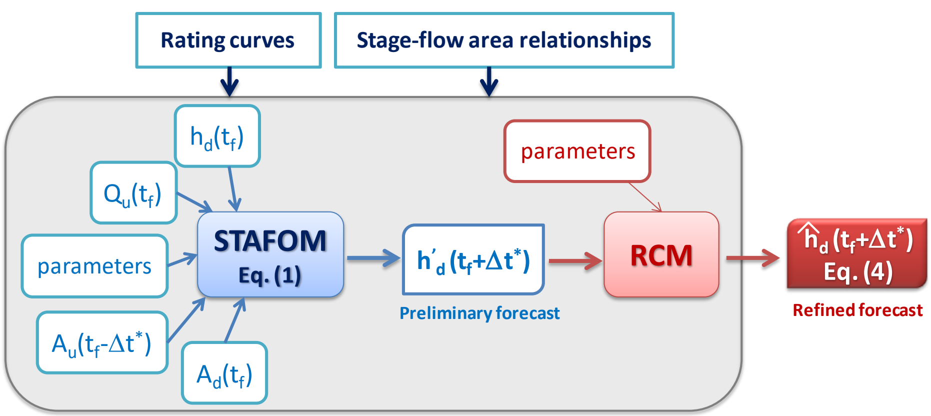

Figure 1 Scheme of the STAFOM-RCM model application.

1) STAFOM, providing a first estimate of the forecast stage (preliminary forecast) at the downstream end, h_d', computed as:

$$h_d'\left(t_f+\Delta t^*\right)=\left\{\frac{1}{\lambda}\left[C_1^*\left(Q_u\left(t_f\right)+q_{for}\left(t_f\right)L\right)+C_2^*\left(h_d\left(t_f\right)\right)^{\delta}\right]\right\}^{1/\delta} \qquad (1)$$

with $h_d(t_f)$=stage observed at the downstream end at t_f, Δt^*=forecast lead-time=mean observed wave travel time of the reach, $Q_u(t_f)$=observed upstream discharge at t_f, L=river reach length, λ and δ= parameters of the downstream rating curve, $Q_d=\lambda(h_d)^{\delta}$. C_1^* and C_2^* refer to the Muskingum parameters K and θ respecting the constraint $\Delta t^*=2K\theta$. q_{for} is the lateral flow contribution for unit channel length estimated as (Moramarco et al., 2005):

$$q_{for}(t_f) = [A_d(t_f) - A_u(t_f - T_L)] \ / T_L \quad (2)$$

where A_u and A_d are the upstream and downstream flow areas, respectively; T_L is the flood wave travel time assumed equal to the lead-time, Δt^*, for forecasting purposes. The lateral flow is considered uniformly distributed along the branch and, hence, the total lateral discharge entering in the reach in the time interval (t_f; $t_f+\Delta t^*$), Q_l, is equal to $q_{for}(t_f)L$.

2) RCM, improving the preliminary forecast stage from STAFOM by exploiting the following relationship between the upstream and downstream discharge, Q_d (Moramarco et al. 2005):

$$Q_d(t+T_L) = \alpha(A_d(t+T_L)/A_u(t))Q_u(t) + \beta \quad (3)$$

where α and β are the RCM model parameters. Specifically, the preliminary forecast stage, h_d', is considered for computing the downstream flow area, A_d', at time ($t_f+\Delta t^*$) and, hence, the quantity $(A_d'(t_f+\Delta t^*)/A_u(t_f))Q_u(t_f)$. Following equation (3), the refined forecast stage is finally derived as:

$$\hat{h}_d(t_f + \Delta t^*) = \left\{\frac{1}{\lambda}\left[\alpha\left[A_d'(t_f+\Delta t^*)/A_u(t_f)\right]Q_u(t_f) + \beta\right]\right\}^{1/\delta} \quad (4)$$

3. STAGE FORECASTING FOR RIVER SITES DOWNSTREAM CONFLUENCES

The criteria that discriminate the applicability of STAFOM-RCM are: 1) the river reach length (wave travel time); 2) the knowledge of section geometry and rating curves; 3) the uniform distribution of lateral flow along the reach. Therefore, a concentrated inflow located close and upstream the channel end, where the forecast stage is of interest, may affect the accuracy of the model prediction. To overcome this issue, we propose an approach that can be applied when at least two gauged sections are located along the tributary. The methodology is based on three main steps:

1. Analysis of the stage time series recorded at sections B e C located on the tributary and on the main channel, respectively (see Figure 2). Estimate of the relationship between the two stage time series $h_C(t+T_L)=f(h_B(t))$, with T_L=mean wave travel time of BC reach.
2. Forecast stage assessment at section B, $h_{for\_B}(t=t_f+\Delta t^*)$, by applying STAFOM-RCM for the reach bounded upstream by section A (see Figure 2). Δt^* represents the mean wave travel time of reach AB along the tributary.
3. Forecast stage assessment at section C, $h_{for\_C}(t_f+\Delta t^*+T_L)$, by exploiting $h_{for\_B}(t_f+\Delta t^*)$ and the estimated relationship $h_C=f(h_B)$. Moreover, the possible backwater effect at section B due to the confluence is preliminary quantified considering the last forecast error, $Dh(t_f)$:

$$h_{for\_B}(t_f + \Delta t^*) = h_{for\_B}(t_f + \Delta t^*) + Dh(t_f) \quad (5)$$

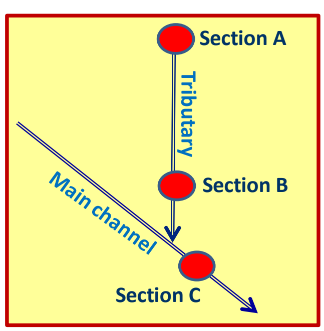

Figure 2 Location of the gauged sections involved in the methodology.

4. CASE STUDY AND DATASET

The Paglia River basin subtended by the hydrometric section of Orvieto is selected as study area. The basin, shown in Figure 3, is located in an inland region of central Italy and has a drainage area of 1277 km^2. The main tributary is the Chiani River (470 km^2). Two hydrometric sections are located on the main river (Allerona and Orvieto), while four gauged stations are operative along the Chiani River.

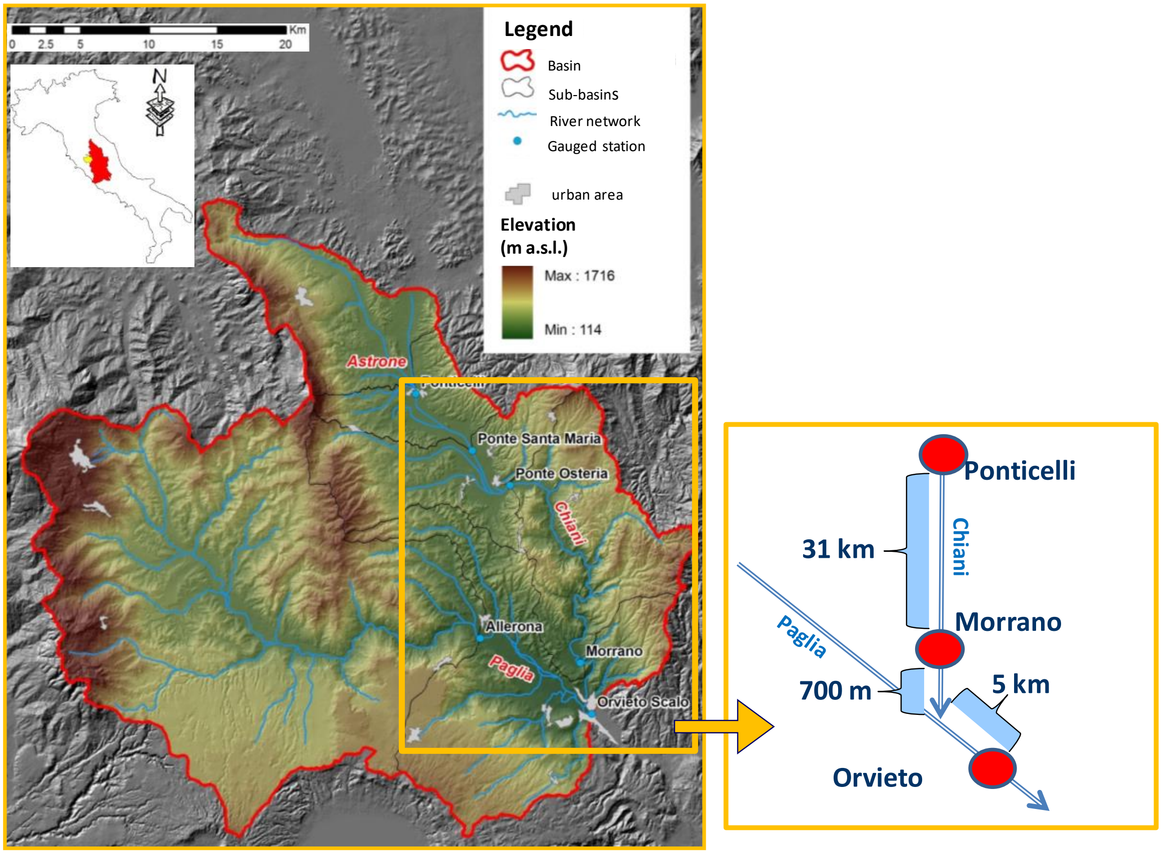

Figure 3 Paglia River basin.

The forecast stage estimate at Orvieto through STAFOM-RCM implemented for Allerona-Orvieto reach is actually not possible for the unavailability of the upstream rating curve and also considering the short distance between the two gauged sections. Moreover, the confluence with the Chiani River, very close to Orvieto site, makes the selected case study non-optimal for the model application. The presence of four gauged sites along the Chiani River, of which Morrano section is immediately upstream the confluence (Figure 3), makes the case study suitable for verifying the proposed methodology. Specifically, Ponticelli station is selected as upstream site and the main properties of the investigated reaches are summarised in Table 1.

Table 1 Main properties of the selected river reaches

reach	upstream drainage area (km²)	downstream drainage area (km²)	intermediate drainage area (km²)	reach length (km)
Ponticelli-Morrano	100	424	324 (76%)	31
Morrano-Orvieto	424	1277	853 (67%)	5

The main flood events recorded during the last decade are selected for the analysis and the main characteristics are shown in Table 2. The highest flood, occurred on November 2012, caused extensive flooding. It is worth noting that the lateral flow between Morrano and Orvieto section is on average very high (≅76%) due to the contribution flowing along the main channel that makes the estimate of the travel time along the selected reach tricky. Specifically, for most floods the rising limb at Orvieto is found contemporary or even earlier than the one observed at Morrano site.

5. RESULTS

The procedure for forecast stage estimate at river sites located downstream confluences is applied for the selected study area in the Paglia River basin.

First, the stage data recorded at Morrano and Orvieto sections during the 11 selected flood events, listed in Table 2, are analyzed and the relationship between them is assessed by considering T_L=0. Figure 4 shows that the stage data are highly correlated allowing to identify a reliable relationship (blue line); however, since a limited data scattering can be observed the upper and lower limit of a band including 95% of the observed points are also identified (red lines).

Table 2 Main characteristics of the selected floods

date	Ponticelli		Morrano		Ponticelli-Morrano		Orvieto		Morrano-Orvieto
	h_{max} (m)	Q_{max} (m^3s^{-1})	h_{max} (m)	Q_{max} (m^3s^{-1})	T_L (h)	lateral flow (%)	h_{max} (m)	Q_{max} (m^3s^{-1})	lateral flow (%)
Nov 25, 05	3.68	47	3.4	252	6	80	6.85	1150	82
Dec 5, 08	2.84	25	1.78	60	4	70	4.90	581	83
Dec 11, 08	2.85	25	2.38	117	2	78	5.09	620	79
Dec 16, 08	2.52	20	1.78	60	4	71	4.37	470	82
Jan 2, 10	2.45	18	1.73	57	4	70	3.59	316	81
Jan 6, 10	4.07	61	3.11	214	4	76	6.98	1195	79
Nov 12, 12	4.49	77	5.18	489	1.5	84	9.68	2663	75
Jan 21, 13	2.86	26	1.44	38	4	62	3.77	270	79
Feb 12, 13	2.82	25	1.65	51	4	65	3.45	231	60
Jan 31, 14	2.65	20	1.68	53	4	62	3.34	218	70
Feb 11, 14	3.04	30	2.08	85	4.5	75	4.23	328	74

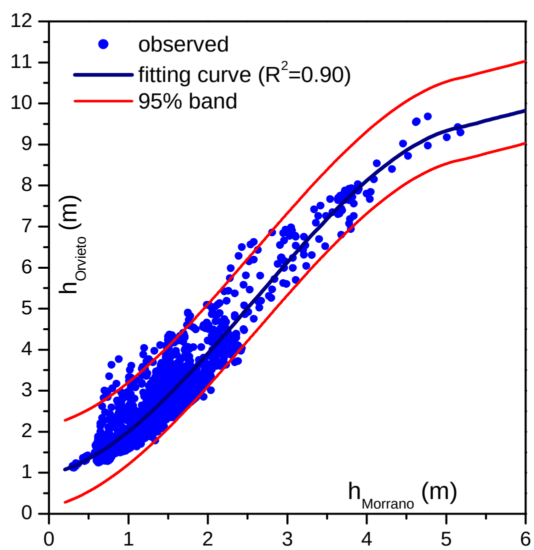

Figure 4 Relationship between hydrometric levels recorded at Morrano and Orvieto gauged sections.

Table 3 Forecast accuracy: error on peak stage, e_h_p, and percentage of observed points included in the band

date	Morrano	Orvieto	
	e_h_p (m)	e_h_p (m)	% included points
Nov 25, 05	0.23	0.61	87
Dec 5, 08	0.13	-1.10	70
Dec 11, 08	0.60	1.00	98
Dec 16, 08	0.12	-0.65	80
Jan 2, 10	0.16	0.08	94
Jan 6, 10	0.38	0.19	90
Nov 12, 12	1.00	0.25	93
Jan 21, 13	0.23	-0.55	78
Feb 12, 13	0.28	0.31	80
Jan 31, 14	0.29	0.29	93
Feb 11, 14	0.28	0.47	89
Mean absolute value	**0.33**	**0.50**	**87**

Second, the forecast stage at Morrano site is obtained through STAFOM-RCM implemented for Ponticelli-Morrano reach with a lead-time of 4 hours and taking the backwater effect into account, due to the close confluence with the Paglia River (≅700 m),

considering the last error on forecast stage. The model performance is found satisfactory with a mean error on peak stage equal to 0.33 m (Table 3) and a good accuracy on the prediction of flood hydrograph for most investigated events (Figure 5).

Third, the forecast stage at Orvieto site is derived exploiting the forecast at Morrano and the relationship between the stage values recorded at the two gauged stations at the same time. The accuracy of the future predictions can be seen in Table 3 where the error on peak stage equal, on average, to 0.50 m, has shown along with the percentage of observed points included within the band shown in Figure 4. It is worth noting that the mean value equal to 87% can be considered satisfactory because, actually, the band is not the result of statistical analysis and, therefore, it is not associable with a percentage of relevance on the basis of which it should be verified. By way of example, Figure 5 shows the results for some events. For the high flood of November 2005 (Figure 5a), a slight overestimated and delayed forecast peak stage can be observed at both sections. However, 87% of the points observed at Orvieto site is within the band including the whole all peak region. The lower flood in Figure 5b is accurately predicted at Morrano site and even if a delay is found for the downstream section, but the observed hydrograph is almost completely within the band limits. The highest event, shown in Figure 5c, is accurately forecasted at Orvieto even if the forecasted peak stage at Morrano is 1 m above the observed one.

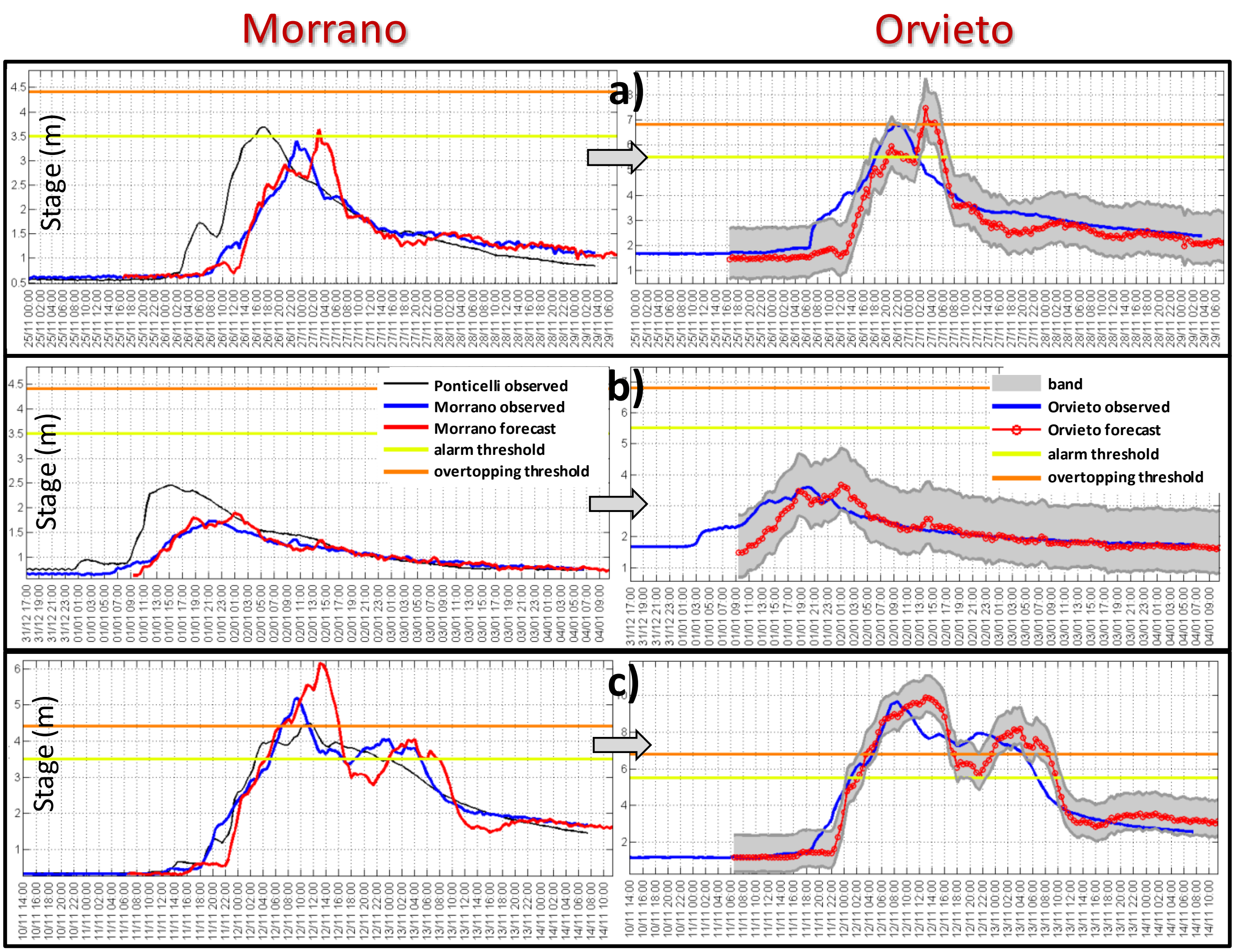

Figure 5 Morrano and Orvieto section: comparison between observed and forecast stages for: a) Nov. 25, 2005; b) Jan. 2, 2010; c) Nov. 12, 2012. The band assessed through the stage relationship is also shown at Orvieto.

The analysis on the model capability to correctly forecast the exceeding or non-exceeding of available hydrometric thresholds is also carried out and shown in the contingency table (Table 4). As it can be seen, for the 11 investigated floods, the overtopping threshold is exceeded during 1 and 3 events at Morrano and Orvieto section, respectively, and it was correctly predicted by the model for all of them. Moreover, also all the non-exceedance thresholds are successfully catched.

Table 4 Contingency table: model capability in hydrometric thresholds exceedance/non-exceedance prediction

Morrano (overtopping threshold=4.4 m)				
		observed		total
		Threshold exceedance	Threshold non-exceedance	
forecast	Threshold exceedance	1 (Hits)	0 (False alarm)	1
	Threshold non-exceedance	0 (Misses)	10 (Correct non-events)	10
Total		1	10	11
Orvieto (overtopping threshold=6.8 m)				
		observed		total
		Threshold exceedance	Threshold non-exceedance	
forecast	Threshold exceedance	3 (Hits)	0 (False alarm)	3
	Threshold non-exceedance	0 (Misses)	8 (Correct non-events)	8
Total		3	8	11

6. CONCLUSIONS

The issue of lateral flow representation in flood forecasting modelling is investigated in this paper. Specifically, a methodology for future stage predictions at gauged sections located downstream river confluences is proposed. The procedure is based on the forecast stages provided by STAFOM-RCM model at a site along the tributary and on the relationship between the stages recorded at this site and at the downstream section on the main channel. The results obtained for the case study selected in the Paglia River basin, central Italy, demonstrate that the methodology can be, on the one hand, useful for real-time hydraulic risk management in flood-prone areas located downstream river confluences provided that gauged sites are operative along the tributary and, on the other hand, easily transferable to different context of natural channels due to its simplicity and the limited parameters required.

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